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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
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July 24, 1967

Mr. Lloyd C. Fowler, Chief Engineer
Santa Clara County Flood Control and
Water District
70 West Hedding Street
San Jose, California, 95110

Dear Mr. Fowler:

The enclosed paper, "Analog-Model Study of the Ground-Water Reservoir in the Santa Clara Valley, California," by P. R. Wood, is forwarded for your information before its presentation at the San Jose Engineers Club by Mr. Wood August 15. The paper has been submitted to the Director of the U.S. Geological Survey for approval for release to the open file. Pending such approval, it is for your use only and should not be released to the general public.

The paper describes briefly the electrical circuitry proposed for the analog model being constructed by the Geological Survey, in cooperation with the Santa Clara County Flood Control and Water District; presents basic assumptions required for simplification of the complex aquifer system; and outlines information needed for construction, verification, and refinement of the analog model.

At the request of your office, work done on the analog-model project during the period July 1, 1966, through June 30, 1967, is summarized below:

1. Available well data (drillers' logs, geophysical logs, well-location maps, water levels, information on the depths, yield, specific capacity, and use) have been collected from the files of the U.S. Geological Survey, California Department of Water Resources, Santa Clara County Flood Control and Water District, Santa Clara Valley Water Conservation District, and municipalities in the San Jose metropolitan area.

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7. Base maps (scales, 1:48,000 and 1:62,500), showing drainage, culture, main-traveled roads, and the California Department of Water Resources township, range, and section grid, have been prepared on scale-stable material.

8. A hydrogeologic map, showing principal water-bearing units in the Santa Clara Valley, has been prepared from existing geologic maps.

9. A map showing our best estimate of the transmissibility of the water-bearing deposits in the Santa Clara Valley north of Coyote Gorge has been prepared from specific-capacity information and from pumping tests made by the California Department of Water Resources.

10. A map showing the piezometric surface of the ground-water reservoir, as of 1914-15, has been prepared from information contained in U.S. Geological Survey Water-Supply Paper 519 and from other published and unpublished sources.

11. Hydrologic-inventory calculations for the period 1934-60 were made to determine the recharge-discharge relation under steady-state conditions.

12. A method was developed for determining the rate of land-surface subsidence. The electrical circuitry necessary for testing the applicability of the method to land subsidence in the Santa Clara Valley is now being tested in Phoenix, Ariz.

13. A hydrogeologic map, a transmissibility map, a piezometric map as of 1914-15, and maps showing three different interpretations of the recharge-discharge relation under conditions that existed in 1914-15 have been sent to Phoenix. These maps should provide information needed for the analog-model unit in Phoenix to prepare and test an analog model under conditions assumed to have existed in 1914-15. When the analog model has been constructed to reflect as accurately as possible conditions that existed in 1914-15, wells will be simulated and "pumped" at specified rates, and water-level declines indicated by the model will be checked against actual known declines.

We feel that satisfactory progress has been made on the project during the past year, especially when one considers the large quantity of data from a myriad of sources that must be tabulated, sorted, and analyzed before they can be used.

Please feel free to contact us if you desire any additional information regarding the project.

Very truly yours,

R. Stanley Lord

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R. Stanley Lord
District Chief

Enclosure

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2. Municipal pumpage has been collected and compiled for all known pumping stations in the San Jose metropolitan area. Wherever possible, pumpage has been compiled in tables showing quantities of water pumped (in acre-feet) each year that the various pumping stations have operated. Pumping data were obtained from municipalities, California Department of Water Resources, California Public Utilities Commission, California Municipal Statistics, Inc., reports published by the U.S. Geological Survey, State of California, and private agencies.

   Data on agricultural pumpage have been obtained from the Santa Clara Valley Water Conservation District and from published reports.

   Data on industrial pumpage are very incomplete. Our present information will allow little more than a rough estimate of quantities pumped.

   Computer-punched well-data cards, furnished by the Santa Clara County Flood Control and Water District have been machine-sorted as to use of water and date the pumped wells were drilled. Computer printouts of these data are our best source of information.

3. Maps and other information on land use have been obtained from the Santa Clara County Planning Commission, California Department of Water Resources, and tricounty reports prepared by Creegan and D'Angelo.

4. Records of ground-water levels in observation wells measured by the Santa Clara Valley Water Conservation District were obtained, and long-term records from about 80 (shallow and deep) wells in the confined and unconfined parts of the aquifer system were prepared for computer processing. Utilizing an existing Geological Survey computer program, computer-printed hydrographs showing long-term water-level fluctuations were prepared for use in determining rates of water-level decline and total water-level decline in various parts of the valley.

5. Data on the thickness of clay and the thickness of water-bearing materials are being compiled from well logs. At present, data have been compiled for most of the area north of the north edge of T. 8 S. The information on thickness of clay and other water-bearing materials will be used to prepare maps that will be useful in determining vertical permeability of clay and transmissibility of other water-bearing materials.

6. Information on the water table in the area north of Coyote Gorge is being compiled from logs of wells, building-foundation borings, State and county highway borings, and other sources. At present, data have been compiled for most of the area north of Stevens Creek Blvd. The water-table information will be useful in determining where and how much the water table has declined in response to water withdrawals from the confined water body.

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ANALOG-MODEL STUDY OF THE GROUND-WATER RESERVOIR IN THE SANTA CLARA VALLEY, CALIFORNIA[1]

By P. R. Wood[2]

INTRODUCTION

Ladies and gentlemen, it is a pleasure to be invited to appear before the Engineers Club of San Jose and explain a part of the work that the Water Resources Division of the U.S. Geological Survey is doing in the Santa Clara Valley.

I would like to present basic assumptions required for simplification of the complex aquifer system in the Santa Clara Valley, and outline the data required for the construction and verification of the electric-analog model of the ground-water reservoir now being constructed by the Geological Survey, in cooperation with the Santa Clara County Flood Control and Water District.

The purpose of building the analog model is to provide a tool to analyze the response of the hydrologic system under various simulated conditions. The various choices of water management or development can then be evaluated on the basis of information that is pertinent and can be defined.

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[1] Approved by the Director of the Geological Survey for release to the open file August 1967.

[2] Hydrologist, Water Resources Division, U.S. Geological Survey, Menlo Park, California.

ANALOG MODEL

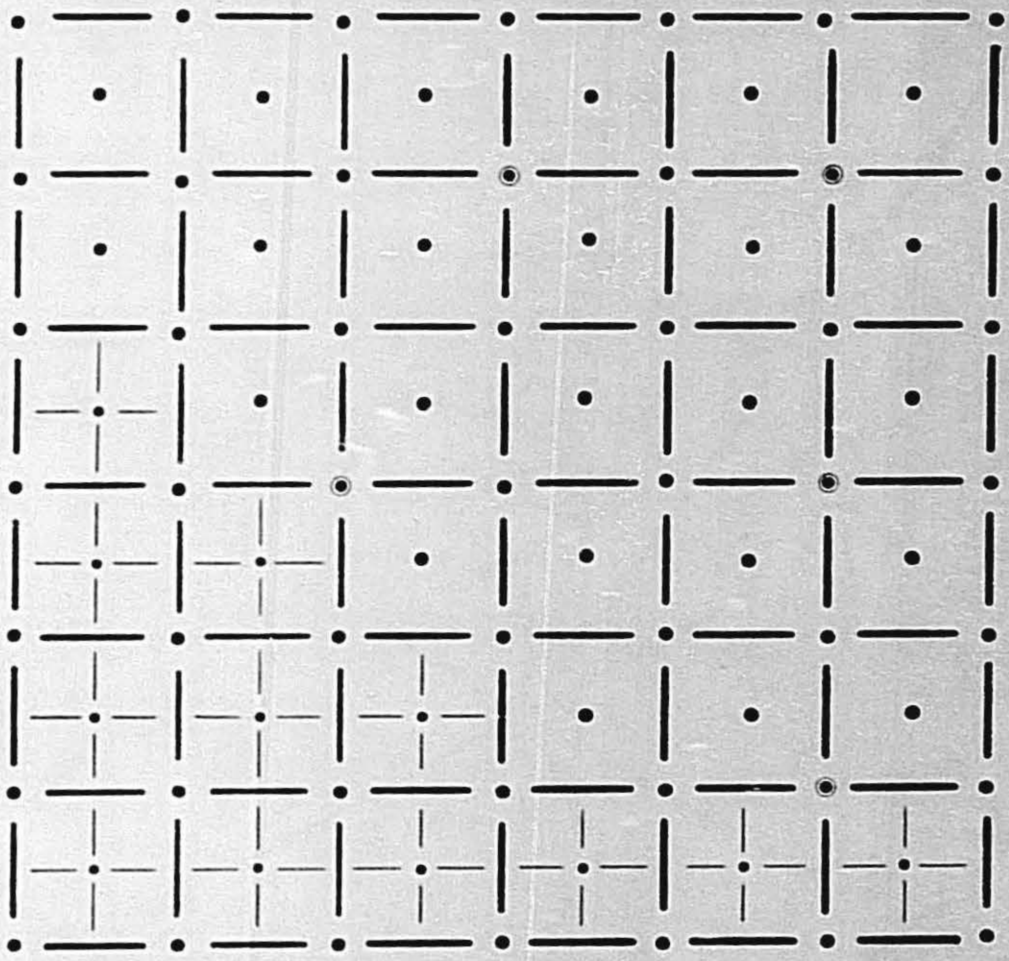
An analog model is a computing device that is a physical analogy of the problem to be solved. Models of this type are used by many branches of science where it is more convenient to use or measure the parameters of another physical system, rather than the one of direct interest. In water resources investigations, where the occurrence and movement of underground water is of major concern, the hydrologist commonly chooses the electrical analogy because physical laws governing the flow of electricity through a network of resistors and capacitors have the same mathematical form as laws governing the movement of water in a ground-water reservoir. A resistor, in an electrical circuit, impedes the free flow of current; just as in nature, rocks and other permeable materials impede the free flow of water. Similarly, a capacitor in a circuit stores and releases electrical energy in a manner comparable to the storage and release of water in permeable rocks and deposits. These and several associated analogies used by the hydrologist are shown below.

Electrical quantities	Physical quantities
Voltage	Head
Amperage	Discharge
Resistance	Permeability
Capacitance	Storage coefficient
Time, in seconds	Time, in days

Figures 1 and 2 show the proposed circuitry for the analog model of the Santa Clara Valley. The functions of the various electrical components are described in table 1.

U S GEOLOGICAL SURVEY

FIGURE 1



EXPLANATION

● Holes, ½-inch center, in pegboard

◉ Model well

━ Resistor, 1-inch (basic) grid

— Resistor, ½-inch (detail) grid if needed

Capacitors, vertical-leakage network, and recharge and discharge elements not shown. See figure 2 for diagram showing electrical flow circuit at model-well nodes.

Diagram showing basic resistor network proposed for Santa Clara Valley analog model. Scale, 2 inches per mile.

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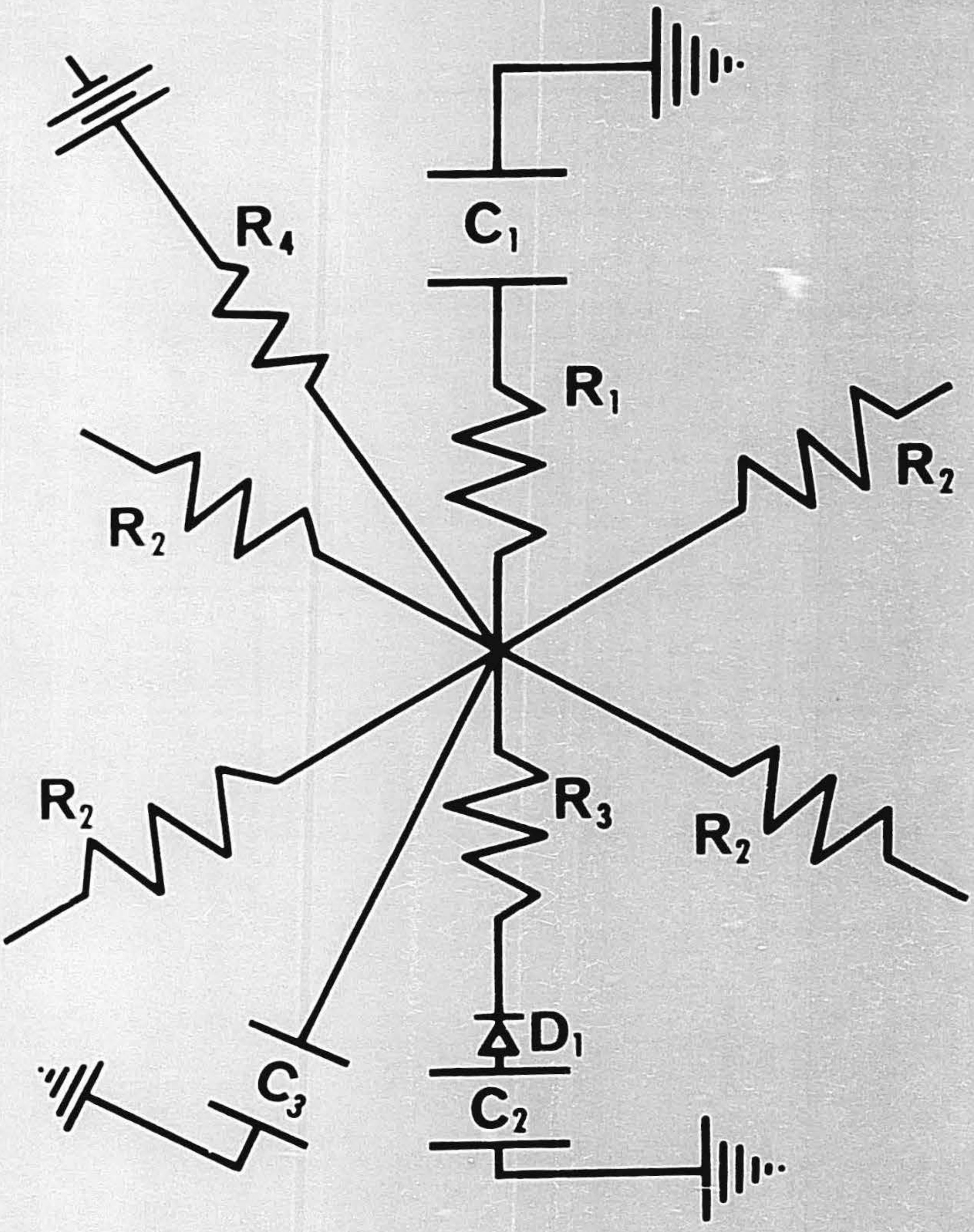

Diagram of proposed electrical flow circuit for confined aquifer system.
Functions of electrical components summarized in table 1.

Table 1.--Functions of electrical components

Electrical components	Function
Capacitor, C_1	Water contributed from storage in confining layer (water-table aquifer and semiconfined to confined zone above the top of the heavily pumped zone).
Resistor, R_1	Effective vertical permeability of deposits in confining layer.
Resistor, R_2	Transmissibility of heavily pumped zone (interval tapped by most large-capacity wells).
Capacitor, C_2	Water contributed from storage in heavily pumped zone (chiefly from compaction of clay).
Resistor, R_3	Permeability of clay in heavily pumped zone.
Capacitor, C_3	Water contributed from artesian storage in heavily pumped zone.
Resistor, R_4	Water withdrawal per unit of time by a well or group of wells (used as model wells).
Diode, D_1	Effects unidirectional movement of water from compacted clay.
	Electric currents simulating recharge (from precipitation and percolation ponds) to be added to model at appropriate places and at rates comparable with natural conditions.

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When constructed, the analog model will represent the hydrologists' interpretation of the hydrologic environment. If the conceptual model developed by the hydrologist is correct, known stresses (water inputs and withdrawals) may be related to observed effects (water-level changes or land subsidence) in the same manner that stresses and effects are related in the actual ground-water reservoir. If the analog model does not reproduce the actual observed effects, the hydrologists' conceptual model is incorrect and must be reevaluated. This feedback procedure is continued until a satisfactory analogy is obtained.

Checking and verification of the model require data on:

1. Location, history of use, and water withdrawn per unit of time by each well, or group of wells, used as a model well.

2. Changing patterns of water use, crop surveys, growth of urban areas, and industrial parks to be used as an aid in establishing rates of water withdrawal during specified periods of time.

3. Infiltration from precipitation and excessive irrigation in the forebay areas, where these sources of recharge effectively add to the available water supply in the heavily pumped zone.

4. Percolation from stream channels, ponds, and other water-spreading operations in the forebay area; where the heavily pumped zone is confined, as it is in much of the valley, percolation is not a source of recharge to the heavily pumped zone and will not be modeled.

5. Subsurface inflow of water to area of interest; includes water that moves through Coyote Gorge, water from the formations exposed along margins of valley, and, possibly, water from the alluvial fan of San Francisquito Creek.

6. Subsurface outflow of water from the area of interest; includes evapotranspiration in the marshes bordering San Francisco Bay and possibly movement of water into older formations in San Francisco Bay and (or) the alluvial fan of San Francisquito Creek.

7. Water-level changes (declines or rises during specified periods of time) that have occurred as a result of water withdrawals for agriculture, municipal, and other uses.

8. Land-surface subsidence rates, from which water contributions due to clay compaction can be computed.

Basic Assumptions

In developing the conceptual model of the Santa Clara Valley, we have assumed that:

1. The geologic units of significance include: The Bay mud, beds and lenses of clay, and other fine-grained deposits near the margins of San Francisco Bay; alluvial deposits of undetermined thickness in the Santa Clara Valley; the Santa Clara Formation and deposits of related age that are exposed locally around the margin of the valley and presumably underlie younger alluvial deposits in the valley area; and the Purissima Formation, where this unit is in contact with alluvial deposits. Formations other than those mentioned are poorly permeable and contribute insignificant quantities of water.

2. The water-bearing formations in the Santa Clara Valley are separated from water-bearing formations under San Francisco Bay and from those in the Niles Cone by beds of silt and clay that become thicker, more extensive, and more fine grained toward the bay.

3. The heavily pumped zone (interval tapped by most large-capacity wells) may be simulated by one layer, even though the zone itself consists of several layers containing water under different heads. The head differs from place to place chiefly because the horizontal and vertical distribution of pumpage differs and because lenticular masses of clay and other fine-grained materials retard the vertical equalization of head.

4. Wells tapping the heavily pumped zone fully penetrate the zone so that all the pumpage from the zone can be considered as a unit.

5. True three-dimensional flow can be approximated by purely horizontal flow through the sand and purely vertical flow through the clay.

6. Vertical leakage from the water-table aquifer through the confining layer (which in some areas only partly confines the heavily pumped zone) and from the confining layer itself, is related to the thickness and permeability of the confining layer and to the vertical head difference across it.

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7. The quantity of water contributed from the compaction of clay beds is numerically equal to the total volume of the land subsidence during any given increment of time. The rate of clay compaction is a function of the total number of compacting beds, thicknesses and permeability of individual beds, and the expulsion of pore water in response to head differentials between beds of clay and more permeable materials.

8. The water table (top of zone of saturation) has not changed significantly because percolation along stream channels, recharge from precipitation, and infiltration of irrigation water, in excess of that needed for plant growth, probably offset much of the water lost by vertical leakage and by pumping.

Data Required for Construction and Verification of the Model

The electrical flow circuit diagrammed in figure 2 summarizes the information required for construction of the analog model. Capacitor C_1 (fig. 2) simulates water contributed from storage in the confining layer (water-table aquifer and the semiconfined-to-confined zone between the water table and the top of the heavily pumped zone). As of this date we have meager data on the water-table aquifer. We hope to obtain some information from drillers' logs, water-level measurements from shallow wells, building-foundation borings, and highway-department borings. The top of the heavily pumped zone is another unknown. No single bed of clay or sequence of clays can be recognized as a confining layer. In lieu of such a unit, we propose considering the top of the heavily pumped zone at the top of the perforated interval in large-capacity wells.

Resistor R_1 (fig. 2) simulates the effective vertical permeability of the deposits in the interval between the water table and the top of the heavily pumped zone. The electrical circuit proposed here will allow us to model the leakage if assumption number 8 is reasonably correct. The only information needed to determine the vertical leakage through the confining layer (R_1) is the average vertical permeability of the clay and the rate of water-level decline below the confining layer.

The heavily pumped zone is represented in the model by a resistor net which simulates the transmissibility R_2 (fig. 2) of the water-bearing deposits and by capacitors C_2 (fig. 2) which simulate storage in the clay beds. Each capacitor is connected to the resistor net by a resistor R_3 (fig. 2) which has a value proportional to the permeability, thickness, and number of beds of clay in the heavily pumped zone. The transmissibility (R_2) will be based on specific capacity tests, drillers' logs, and pumping tests made by the Geological Survey and the California Department of Water Resources. Capacitor C_3 (fig. 2) simulates artesian storage in the heavily pumped zone. This capacitor releases an electric current in the same manner as permeable materials (sand and gravel) in the confined aquifer system release water in response to changes in hydrostatic head.

We hope to use the electric current released by capacitor C_2 as one method of verifying the analog model. The current released by this capacitor simulates the water released from layers of clay in response to head differentials created by water withdrawals from the more permeable beds (sand and gravel) in the heavily pumped zone. As water in the clay is released, the clay beds compact and occupy less space in the aquifer system. The area of compacting clay is reflected at land surface by a saucerlike depression that ranges from a fraction of an inch to several feet in depth. We know from accurate surveys how much land subsidence has occurred during certain periods. Hence, if our assumptions and modeling are correct, land subsidence indicated by the analog model should closely approximate subsidence as actually measured in the field.

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Another, and probably most used, method of verifying the analog model is by comparing the magnitude and location of maximum voltage drop, as indicated by the model, for a specific period with the magnitude and location of maximum water-level declines actually observed in the field. We propose using the periods 1914-34, 1914-40, 1914-60, and 1914-66 because, for these periods, water-level records, subsidence data, and pumpage records seem to be reasonably complete.

The aquifer system can be modeled with as much detail as the field data justify. However, much depends upon how accurately we can: (1) Compute and distribute pumpage for agricultural, municipal, industrial, and other uses during the different periods chosen for analysis; (2) determine the various aquifer coefficients; (3) compute recharge that actually reaches the heavily pumped zone; and (4) define the hydrogeologic environment.

DATA NEEDED TO REFINE THE MODEL

The program of basic-data collection, including the gathering of information on new and existing wells, pumpage, water-level measurements and quality of water analyses for wells of various depths, and collection of land-subsidence data should be continued. In areas where the heavily pumped zone functions as a confined aquifer, the program of basic-data collection should be expanded to include water-level measurements in wells of various depths in order to provide data for studies of recharge to the water-table aquifer and of downward movement of water through the confining layer to the heavily pumped zone. More detailed pumping data for wells of various depths should be collected and compiled for use in refinement and modification of the model. Municipalities, certain industries and other large water users generally keep excellent pumpage and water-level records for short periods of years. However, these records tend to become lost, unless interested water agencies collect and compile them for future use.

In summary, considering the large quantity of data from a myriad of sources that must be tabulated, sorted, and analyzed before they can be used we feel that considerable progress has been made, during the past year, on the water-resources study of the Santa Clara Valley.